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B Masses and Lifetimes at the Tevatron

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Abstract. We review recent results of B^{**} masses, mass and lifetime of B_c^+ meson, and lifetimes of B_s^0 and Λ_b^0 hadrons from Tevatron Run II.

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INTRODUCTION

Measurement of masses and lifetimes of the B hadrons provides important test of many theoretical models. Heavy Quark Effective Theory (HQET) gives predictions on mass spectra of orbitally excited B states [1], and Heavy Quark Expansion technique (HQE) calculates lifetime differences among different B hadrons [2]. The mass of B_c^+ meson is also predicted by lattice QCD calculation [3]. Measuring these quantities gives very good test of various theoretical predictions. The Tevatron Run II is a great place to study these B hadron properties. Since 2001, Tevatron delivered about 1.5 fb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV up to February 2006. Both the CDF and D0 detectors have excellent mass and lifetime resolution, and various triggers installed to measure B hadron properties in many aspects. CDF has a displaced track trigger which captures B events by triggering on tracks with large impact parameter. And both the CDF and D0 have lepton triggers, which capture single or di-lepton events. The single lepton triggers are optimized to capture semileptonic B decays, and di-lepton trigger finds B signals associate with J/ψ or Υ resonances. Thanks to large b production rates at the $p\bar{p}$ collision and the excellent triggers, the Tevatron have world's largest B^{**}, B_c^+, B_s^0 and Λ_b^0 samples. In this document we summarize latest results on orbitally excited B states, B_c^+ properties, and lifetimes of B_s^0 and Λ_b^0 hadrons reported by CDF and D0 in Tevatron Run II. Charge conjugate states are always implied thoughout this text.

ORBITALLY EXCITED B MESONS

The ground states of $\bar{b}q$ system are the pseudoscalar and vector states, which have orbital angular momentum $L = 0$ and total spin $S = 0$ or 1. If we consider states with $L = 1$ and combine it with spin $S = 0$ or 1, four different states will be allowed with $J^P = 0^+, 1^+, 1^+$ or 2^+. These orbitally excited states are called as B_0^*, B_1^*, B_1 and B_2^* respectively, and decay to $L = 0$ states with strong interaction. The B_0^* and B_1^* states decay via S-wave and thus have broad width (~ 100 MeV/c^2). Due to such broad width, these states are not yet observed experimentally. On the other hand, the B_1 and B_2^* states decay via D-wave and have narrow width.

Both the CDF and D0 experiments provide the mass measurement of B_1 and B_2^* states using data from the Tevatron Run II. CDF reconstructs B^+ signal using two different decay modes, $B^+ \to J/\psi K^+$ and $B^+ \to D^0\pi^+$ in the data size of 370 pb^{-1} [4]. Then the B^+ candidate is combined with a negatively charged track, and mass difference is calculated as $Q = M(B^+\pi^-) - M(B^+) - M(\pi^-)$. Spectra of the mass difference for two different B^+ decay modes are shown in Figure 1. Peaks observed in the spectra are originated from three different decays of orbitally excited B states. By fitting these spectra with signal and background templates, masses of the B_1 and B_2^* states are measured. The signal template is assumed as non-relativistic Breit-Wigner function convoluted with detector resolution. At the fit, width of the B_1 and B_2^* states are fixed to be a theoretically predicted value. As a result of the fit, masses are obtained to be

$$
\begin{aligned}
M(B_1) &= 5734 \pm 3(stat.) \pm 2(syst.)\ \mathrm{MeV}/c^2 \\
M(B_2^*) &= 5738 \pm 5(stat.) \pm 1(syst.)\ \mathrm{MeV}/c^2.
\end{aligned}
$$

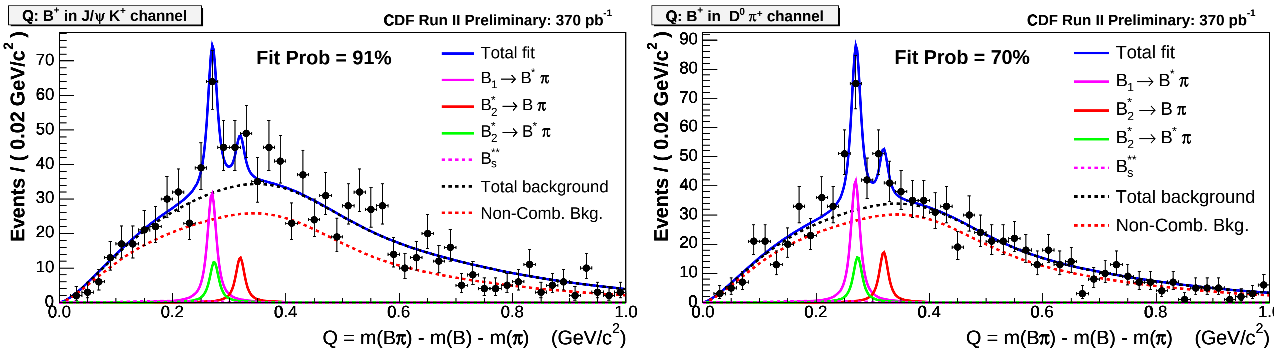

FIGURE 1. Spectra of mass difference with two different B^+ decay modes measured at the CDF in Tevatron Run II. Left: $B^+ \to J/\psi K^+$ sample, Right: $B^+ \to D^0\pi^+$ sample.

The DØ also measures the masses of B_1 and B_2^* states using fully reconstructed $B^+ \to J/\psi K^+$ sample in the data of 1 fb^{-1} [5]. The spectrum of mass difference between $B^+\pi^-$ and B^+ system is shown in Figure 2 left plot. By fitting the spectrum of mass difference, the mass of B_1 and mass difference between B_2^* and B_1 states are measured as

$$\begin{aligned} M(B_1) &= 5720.8 \pm 2.5(stat.) \pm 5.3(syst.)\ \mathrm{MeV}/c^2, \\ M(B_2^*) - M(B_1) &= 25.2 \pm 3.0(stat.) \pm 1.1(syst.)\ \mathrm{MeV}/c^2. \end{aligned}$$

Width of the two narrow states are also measured as

$$\Gamma(B_1) \equiv \Gamma(B_2^*) = 6.6 \pm 5.3(stat.) \pm 4.2(syst.)\ \mathrm{MeV}/c^2$$

assuming $\Gamma(B_2^*)$ and $\Gamma(B_1)$ are identical.

The $J^P = 2^+$ state of the $\bar{b}s$ system, called B_{s2}^{*0}, is recently observed at DØ [6]. The B_{s2}^{*0} signal is fully reconstructed using a decay chain $B_{s2}^{*0} \to B^+K^-$, $B^+ \to J/\psi K^+$ in 1 fb^{-1} of data. A spectrum of mass difference $Q = M(B_{s2}^{*0}) - M(B^+) - M(K^-)$ is shown in Figure 2 right plot. The mass of $M(B_{s2}^{*0})$ state is obtained to be

$$M(B_{s2}^{*0}) = 5839.1 \pm 1.4(stat.) \pm 1.5(syst.)\mathrm{MeV}/c^2.$$

This is the first direct observation of the B_{s2}^{*0} state.

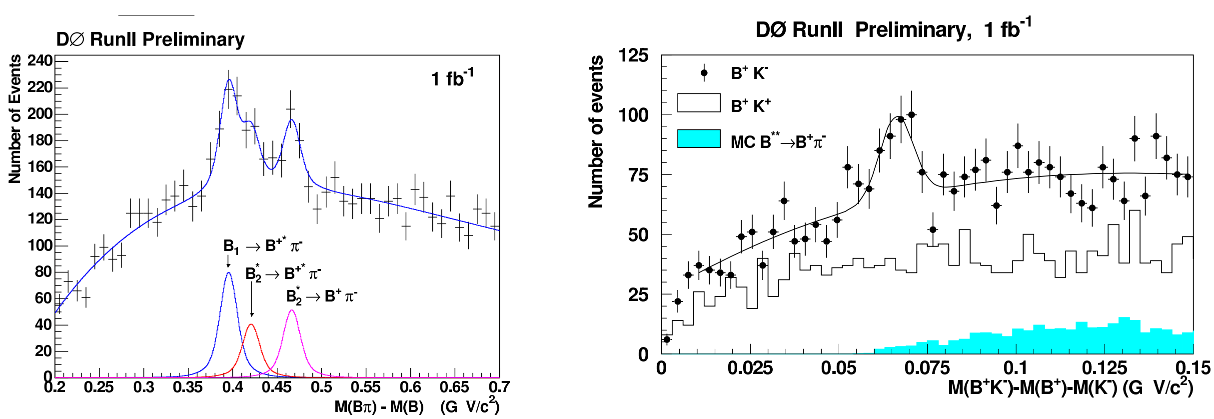

FIGURE 2. Spectra of mass difference measured at DØ in data of 1 fb^{-1}. Left : Mass difference between $B^+\pi^-$ and B^+. Right: Mass difference among B^+K^- and B^+, K^- system.

MASS AND LIFETIME OF B_c^+ MESON

The B_c^+ meson is a bound state of bottom and charm quarks. Since this is the only meson with two different heavy flavors, it can provide interesting tests of some theoretical models. The B_c^+ mass is predicted by a lattice QCD calculation [3], and the lifetime is calculated with a non-relativistic expansion [7]. The B_c^+ meson is first observed at CDF in Tevatron Run I [8], and now precise measurement of mass and lifetime is given by CDF in Run II.

The B_c^+ meson mass is measured using fully reconstructed hadronic decay $B_c^+ \to J/\psi\pi^+$ [9]. In 800 pb^{-1} of Run II data, 38.9 of B_c^+ candidates are found with significance of about 6σ. Left plot in Figure 3 shows invariant mass distribution of $J/\psi\pi^+$ system. Clear peak from the B_c^+ decay is observed. By fitting the invariant mass spectrum, the mass of B_c^+ meson is obtained to be

$$M(B_c^+) = 6275.2 \pm 4.3(stat.) \pm 2.3(syst.)\mathrm{MeV}/c^2.$$

Measurement of the B_c^+ meson lifetime is also performed at CDF Run II using semileptonic decay $B_c^+ \to J/\psi e^+ \nu$ [10]. About 203 of B_c^+ candidates are obtained in 360 pb^{-1} of data. Figure 3 right plot shows pseudo-proper decay length distribution defined as $ct^* = L_{xy}(B_c^+)M(B_c^+)/p_T(J/\psi e^+)$, where $L_{xy}(B_c^+)$ is a decay length of B_c^+ meson measured in perpendicular plane to the $p\bar{p}$ beam axis. By fitting the pseudo-proper decay length distribution, the B_c^+ lifetime is measured to be

$$\tau(B_c^+) = 0.463\ ^{+0.073}_{-0.065}(stat.) \pm 0.036(syst.)\ \mathrm{ps}.$$

These results are currently world best and consistent with almost of theoretical predictions.

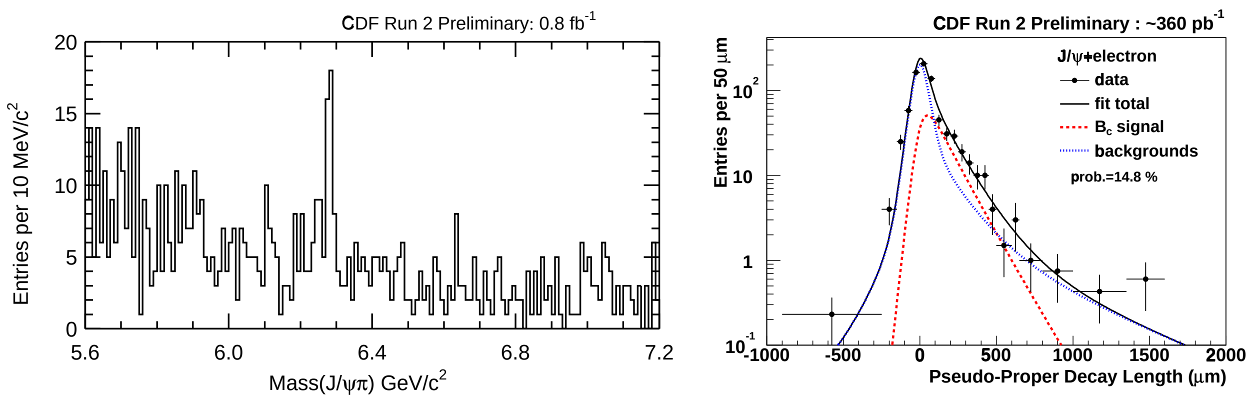

FIGURE 3. Left : The fully reconstructed B_c^+ mass spectrum with the $B_c^+ \to J/\psi\pi^+$ decay mode at CDF. Right : Pseudo-proper decay length distribution of the semileptonic B_c^+ candidates.

B HADRON LIFETIMES

The lifetimes of B hadrons are fundamental and important observable. A theoretical calculation involving non-spectator B hadron decays gives following predictions for lifetime relations [2]:

$$\begin{aligned}
\tau(B^+)/\tau(B^0) &= 1.00 + 0.05 \times (f_B/200\ \mathrm{MeV})^2 \\
\tau(B_s^0)/\tau(B^0) &= 1.00 \pm 0.01 \\
\tau(\Lambda_b^0)/\tau(B^0) &= 0.9 \pm 0.05
\end{aligned}$$

Measuring these ratios is a very good probe to the non-spectator decay mechanism. The ratio of B^+ and B^0 lifetime is already measured with extreme precision by Belle, D0 and BaBar [11], however for the B_s^0 and Λ_b^0 hadrons Tevatron is only the place to measure their properties. In Run II the Tevatron have world's largest samples of these hadrons. In this section we review recent results of the B_s^0 lifetime and lifetime difference between different CP eigenstates from CDF and D0, and the latest Λ_b^0 lifetime result provided by CDF.

Lifetime of B_s Meson

It is known that the B_s^0 and its antiparticle $\overline{B}_s^0$ are mixed each other due to second order weak interaction, and form two CP eigenstates. Assuming no CP violation with the B_s^0 mixing, the CP eigenstates are written as follows:

$$\begin{aligned} |B_{sL}\rangle &= 1/\sqrt{2}\,(|B_s^0\rangle + |\overline{B}_s^0\rangle) \\ |B_{sH}\rangle &= 1/\sqrt{2}\,(|B_s^0\rangle - |\overline{B}_s^0\rangle) \end{aligned}$$

These two states have different mass and lifetimes, the notation L, H means "Light" and "Heavy" mass states. Average and difference of decay width between these states are defined as $\Gamma = (\Gamma_H + \Gamma_L)/2$, $\Delta\Gamma = \Gamma_H - \Gamma_L$, respectively. There are several approaches to determine lifetimes of the $|B_{sL}\rangle$ and $|B_{sH}\rangle$ states. One method is measuring "flavor-specific" lifetime using final states with equal fractions of $|B_{sL}\rangle$ and $|B_{sH}\rangle$ states. The flavor-specific lifetime can be written as

$$\tau(B_s^0)_{\mathrm{fs}} = \frac{1}{\Gamma}\frac{1+\left(\frac{\Delta\Gamma}{2\Gamma}\right)^2}{1-\left(\frac{\Delta\Gamma}{2\Gamma}\right)^2}.$$

Another way is to measure $\tau_L = 1/\Gamma_L$ using $B_s^0 \to K^+K^-$ final state which is 95% originate from $|B_{sL}\rangle$. The last way is measuring $\Delta\Gamma$ directly with $B_s^0 \to J/\psi\phi$ decays separating CP-even and odd components with angular analysis [12]. In this section we review recent results of the former two methods.

The flavor-specific lifetime is measured by both CDF and D0 in Run II using various decay modes. CDF measures the flavor-specific B_s^0 lifetime using semileptonic decay chains $B_s^0 \to D_s^+ \ell^- \overline{\nu}$ ($\ell^- = e^-, \mu^-$) collected by single lepton triggers [13]. It provides high-statistics and good S/N sample. Figure 4 shows D_s^+ mass plot associating with a negatively charged lepton and pseudo-proper decay length distribution for the B_s^0 signal sample. Using about 1150 of partially reconstructed candidates, the B_s^0 meson lifetime and the ratio with $\tau(\overline{B}^0)$ are measured to be

$$\begin{aligned} \tau(B_s^0) &= 1.381 \pm 0.055(stat.)\,^{+0.052}_{-0.046}(syst.)\ \mathrm{ps}, \\ \tau(B_s^0)/\tau(\overline{B}^0) &= 0.938 \pm 0.044(stat.)\,^{+0.049}_{-0.046}(syst.). \end{aligned}$$

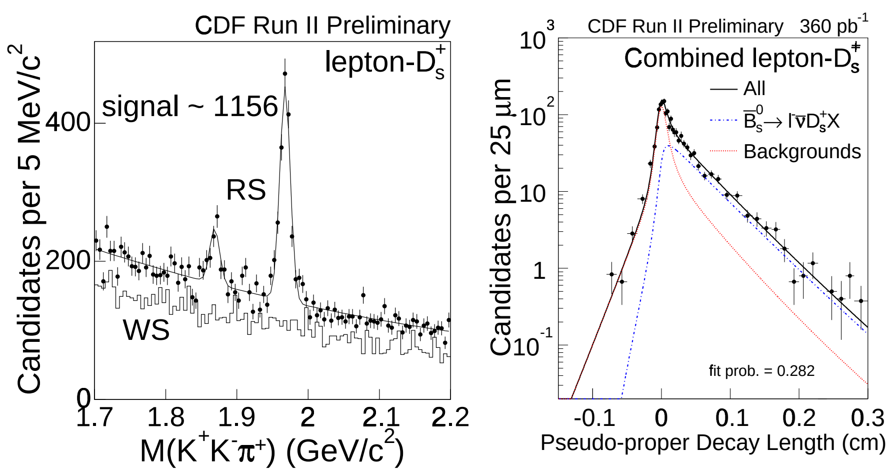

FIGURE 4. Left:Invariant mass spectrum of reconstructed D_s^+ meson associating with a lepton at CDF. Right:Pseudo-proper decay length distribution of the B_s^0 signal sample.

The flavor-specific B_s^0 lifetime is also measured at CDF using the fully reconstructed hadronic decays, $B_s^0 \to D_s^+\pi^-$ or $D_s^+\pi^+\pi^-\pi^+$ in 360 pb^{-1} of data [14]. The data are collected with the displaced track trigger. The displaced track trigger gives bias to the B decay length distribution, therefore the bias is corrected using Monte Carlo simulation. The invariant masses and decay length distributions are shown in Figure 5. In the mass plots one can see the B_s^0 signal peak well separated from other B components. By fitting the mass and decay length spectra simultaneously, the B_s^0 lifetime is obtained to be

$$\tau(B_s^0) = 1.60 \pm 0.10(stat.) \pm 0.02(syst.)\ \mathrm{ps}.$$

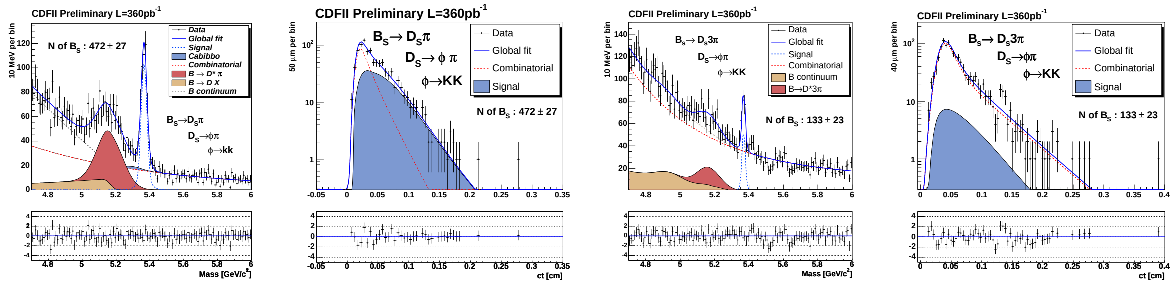

FIGURE 5. Mass and decay length distributions for $B_s^0 \to D_s^+\pi^- / D_s^+\pi^+\pi^-\pi^+$ decay modes at CDF.

Other results of flavor-specific B_s^0 lifetime is provided by D∅ using the semileptonic decay $B_s^0 \to D_s^+\mu^+\nu$ [15]. Thanks to large branching fraction of semileptonic decay and low p_T threshold (> 2 GeV/c) of muon trigger at D∅, large number of B_s^0 candidates are collected. Figure 6 shows mass spectrum of D_s^+ associating with a muon, and pseudo-proper decay length of the B_s^0 sample found in 0.4 fb^{-1} of Run II data. The lifetime is measured as

$$\tau(B_s^0) = 1.398 \pm 0.044(stat.)\ {}^{+0.028}_{-0.025}(syst.)\ \text{ps}.$$

This is the current world's best measurement of the flavor-specific B_s^0 lifetime.

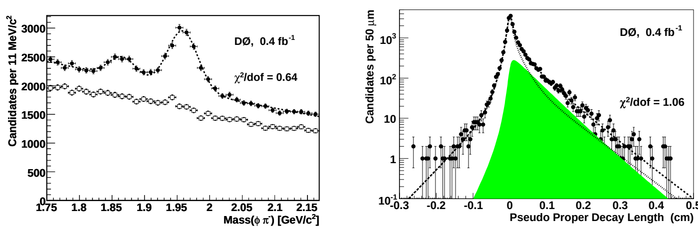

FIGURE 6. Left:Invariant mass spectrum of reconstructed D_s^+ meson associating with a lepton at D∅. Right:Pseudo-proper decay length distribution of the B_s^0 signal sample.

The lifetime of $|B_{sL}\rangle$ state is measured by CDF using the decay $B_s^0 \to K^+K^-$ [16]. Fractions of background B components from $B_d^0 \to K^+K^-/\pi^+K^-$ are estimated from the K^+K^- mass, Kinematics, and particle ID information. Involving the estimated background fractions and shapes into the fit, the lifetime of the $B_s^0 \to K^+K^-$ decay is measured to be

$$\tau(B_s^0 \to K^+K^-) = 1.53 \pm 0.18(stat.) \pm 0.02(syst.)\ \text{ps},$$

and using flavor-specific B_s^0 lifetime taken from the world average, the $\Delta\Gamma/\Gamma$ is found to be

$$\Delta\Gamma_{CP}/\Gamma_{CP}(B_s^0 \to K^+K^-) = -0.08 \pm 0.23(stat.) \pm 0.03(syst.).$$

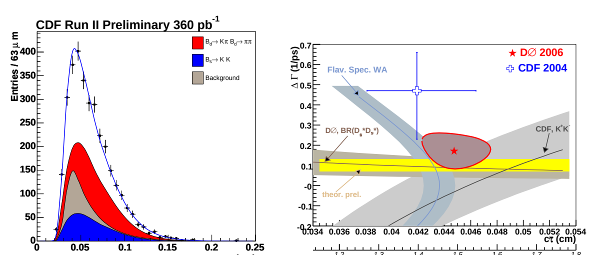

FIGURE 7. Left:The decay length distribution of the $B_s^0 \to K^+K^-$ sample at CDF with various background components overlaid. Right : Summary of various B_s^0 flavor-specific lifetime and $\Delta\Gamma$ measurements.

Lifetime of Λ_b^0 Baryon

The latest result of the Λ_b^0 lifetime measurement is given by CDF using 1 fb^{-1} of data [17]. The decay $\Lambda_b^0 \to J/\psi\Lambda^0$ is analyzed in the di-muon ($J/\psi \to \mu^+\mu^-$) trigger dataset, and 542 of Λ_b^0 candidates are fully reconstructed. The reconstructed mass and proper decay length of the Λ_b^0 are shown in Figure 8. The lifetime of Λ_b^0 is obtained to be

$$\tau(\Lambda_b^0) = 1.593\ ^{+0.083}_{-0.078}(stat.) \pm 0.02(syst.)\ \text{ps},$$

and using world average value of $\tau(B^0)$, the lifetime ratio is obtained to be

$$\tau(\Lambda_b^0)/\tau(B^0) = 1.037 \pm 0.058.$$

These results are currently world's best one. The lifetime ratio $\tau(\Lambda_b^0)/\tau(B^0)$ is measured to be above 1, which shows about 1.8σ discrepancy with the HQE prediction [2], and deviates about 3σ from the current world average [11]. It could give an impact to the theoretical calculation, however more experimental inputs will be needed to conclude the issue.

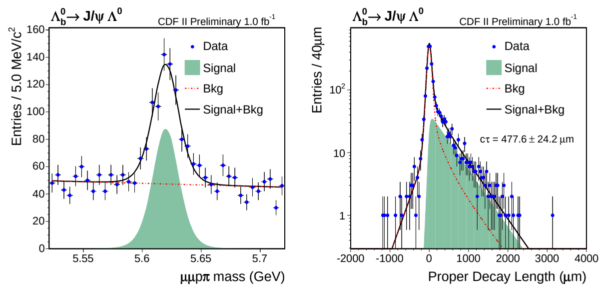

FIGURE 8. Mass and proper decay length distributions for the decay $\Lambda_b^0 \to J/\psi\Lambda^0$ at CDF in Run II.

CONCLUSION

The Tevatron is a great place to study various B hadron properties. In Tevatron Run II, both the CDF and DØ already accumulate more than 1 fb^{-1} of $p\bar{p}$ collision data. Now the measurements of orbitally excited B state masses and properties of the B_c^+ meson enter the stage of precise measurement, and many interesting results with B_s^0 and Λ_b^0 hadrons are being provided. All of these results will give very good tests of the various theoretical prediction. Updates of several analyses are ongoing with the accumulated data, and more interesting results are expected in near future.

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